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Representative Heterogeneity Indicators for Fluvial Geothermal Reservoir Simulation

Yuan Chen[1]*, Guillaume Rongier[1], Denis Voskov[1,2] and Alexandros Daniilidis[1]
Delft University of Technology[1]*, Stanford University[2]
y.chen-21@tudelft.nl

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INTRODUCTION

Direct-Use Geothermal Systems (DUGS) are increasingly installed worldwide for direct heating and cooling and they become more competitive compared to hydrocarbon systems (Lund & Toth, 2021). DUGS mainly targets the deep sedimentary environment, which is water-dominated, at depths around 1.5 km to 3 km with a temperature below 150 degree Celsius (Barbier, 2002). One of the typical reservoir rock types of these systems is fluvial clastic sequence (Moeck, 2014) because of the known good porosity and permeability.

Geological facies modeling is a fundamental approach in reservoir characterization, aiming to represent the subsurface spatial property distribution (Ringrose, 2014). There are two commonly used facies modeling techniques, Object-based modeling (OBM) utilized the predefined objects to better represent the geological structures e.g., channels (Holden et al., 1998) and the the objects are placed randomly in the domain. Another technique is Process-based modeling (PBM) placed the objects based on simplified natural geological processes such as sediment transport, deposition, and erosion responsible for spatial facies distribution (Cojan et al., 2005). The subsurface facies distribution, which directly controls the heterogeneity characterization, has a large impact on the fluid flow and subsequently affects the geothermal systems' performance (Major et al., 2023). Lorenz coefficient is applied to assess the geological heterogeneity level of the static geological models (Tiab & Donaldson, 2016). After the construction of the static geological models with different heterogeneity levels, we perform numerical simulations to check the effect of different geological modeling approaches on thermal production. Open-DARTS (Delft Advanced Research Terra Simulation) has been thoroughly validated against other numerical simulators for geothermal simulation (Wang et al., 2020). The system lifetime and economic outputs from the dynamic simulations are used as quality indicators to assess the performance of the geothermal system. The objective of this work is to quantitively define a N/G ratio threshold from a reservoir engineer's point of view. This threshold helps geologists decide if the detailed geological characterization is required. Geological models with varying overall N/G ratios are constructed to represent different levels of heterogeneity which captures different geological details. As the overall N/G ratio increases, the quality indicators produced by different geological modeling approaches begin to converge. The convergence of these two indicators establishes a quantitative criterion for determining the heterogeneity threshold above which detailed geological characterization can be disregarded.

1 METHOD

Mass and energy conservation equations are applied to describe the thermal multiphase flow in a geothermal production system.

$$\frac{\partial}{\partial t}\left(\varphi\rho_w\right) - \nabla\left(K\frac{\rho_w}{\mu_w}\left(\nabla p_w - \gamma_w \nabla D\right)\right) + \rho_w q_w \sum_{j=1}^{n_p}\rho_j q_j = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\varphi\rho_w U_w + (1-\varphi)U_r\right) - \nabla\left(Kh_w\frac{\rho_w}{\mu_w}\left(\nabla p_w - \gamma_w \nabla D\right)\right) + \nabla\left(\kappa\nabla T\right) + \rho_w q_w h_w = 0 \tag{2}$$

where: φ is porosity [-], ρ_w is water molar density [kmol/m3], U_w is water internal energy [kJ], U_r is rock internal energy [kJ], h_w is water enthalpy [kJ/kg], κ is thermal conductivity [kJ/m/day/K], K is permeability tensor [mD], μ_w is water viscosity [cp], p_w is pressure [bar], γ_w is water gravity vector [N/m3], D is depth [m]. The governing equations are solved by applying Operator Based Linearization (OBL) in open-DARTS (Voskov et al., 2024) framework implicitly.

In this work, we first utilized different facies modeling approaches to build an ensemble of 3D geological facies models (Figure 1A and Figure 1B) based on a range of overall Net-to-Gross (N/G) ratio values. A single process-based facies realization shows 9 facies: Mud plug (MP), Overbank (OB), Levee (LV), Crevasse splay II (CSII), Crevasse Splay II channels (CCh), Crevasse splay I (CSI), Sand plug (SP), Point bar (PB) and Channel lag (CL). b) A single object-based facies realization shows 5 facies: Floodplain (FP), Channel fill (CF), Channel outline (CO), Levee (LV) and Crevasse splay (CS). We then computed 2D vertical N/G ratio maps for each of the realizations created by different approaches. Subsequently, we utilize a set of well N/G ratios and a fixed well spacing to crop the regional facies models followed and applied Sequential Gaussian Simulation (SGS) to populate the porosity for each facies (Figure 1C and Figure 1D). The Lorenz coefficient is used to assess the heterogeneity level of the cropped models. Then we used numerical simulations to investigate the effect of geological heterogeneity on the thermal response of DUGS development by checking the system lifetime and Levelized Cost of Heat (LCOH), Lastly, we investigated the effect of different upscaling techniques on the thermal response of DUGS.

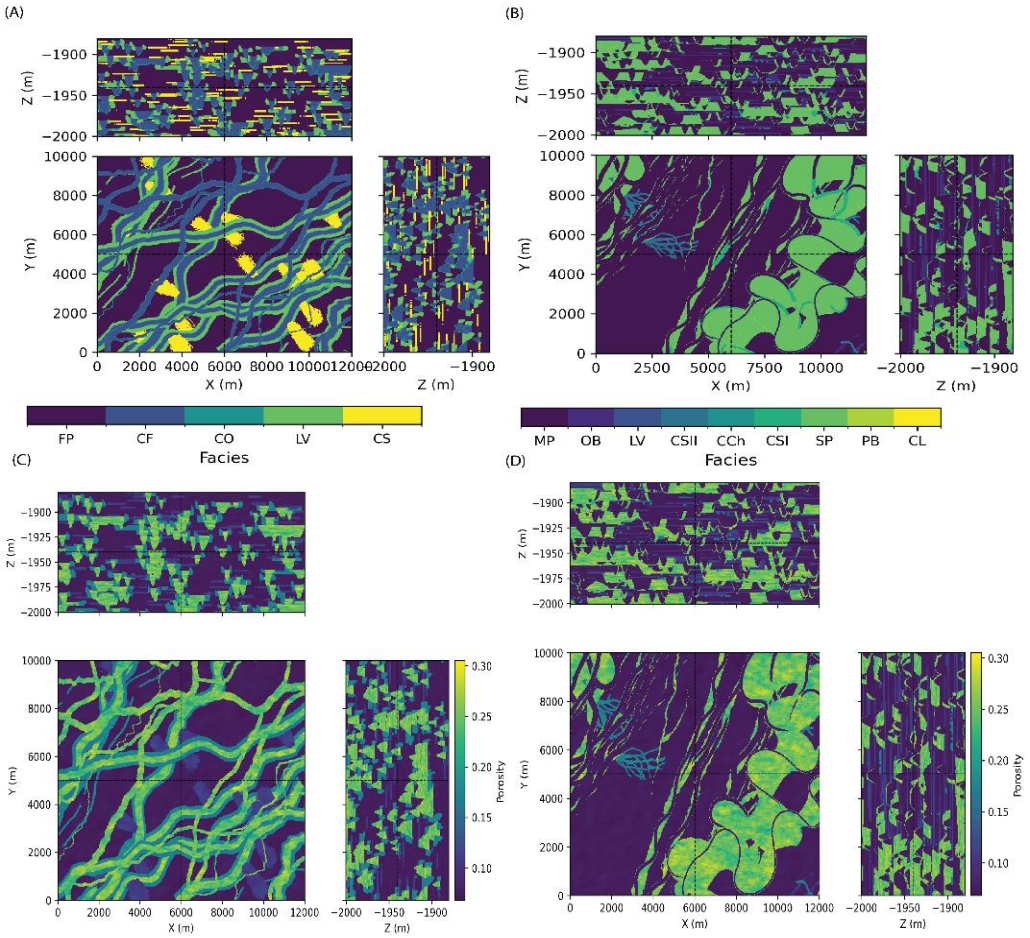


Figure 1. The middle layer of the facies models and corresponding porosity models: (A) facies model created by OBM where (C) is the corresponding porosity model; (B) is the facies model created by PBM where (D) is the corresponding porosity model.

Table 1 describes the main parameters used for the models. We used the optimal numerical setup we found in (Chen et al., 2025) to define the geological resolution. The initial conditions of pressure and temperature of all models follow the respective natural gradients. The rock properties are assigned separately for sandstones and shales.

Table 1. Input parameters for dynamic simulation

Parameter	Value
Regional model grid dimension	600 × 500 × 120
Cropped model grid dimension	200 × 200 × 120
Grid size, m	20 × 20 × 1
Permeability, mD	(0.004–2560)
Porosity, -	(0.01–0.32)

Sandstone heat capacity, kJ/m^3/K	2450
Sandstone heat conductivity, W/m/K	3
Shale heat capacity, kJ/m^3/K	2300
Shale heat conductivity, W/m/K	2.2
Injection temperature, K	300
Well spacing, m	1200
Injection/production rate, m^3/day	8400

2 RESULTS

In total, we have 1354 and 1356 cropped models for PBM and OBM cases. Next, we employ the Lorenz coefficient (LC) and Dijkstra-Parsons (DP) coefficient to assess the heterogeneity level of all cropped realizations. Figure 2 shows that our models cover a large range of heterogeneity levels for OBM and PBM cases with the same overall N/G ratio range and apply the same porosity realization from SGS.

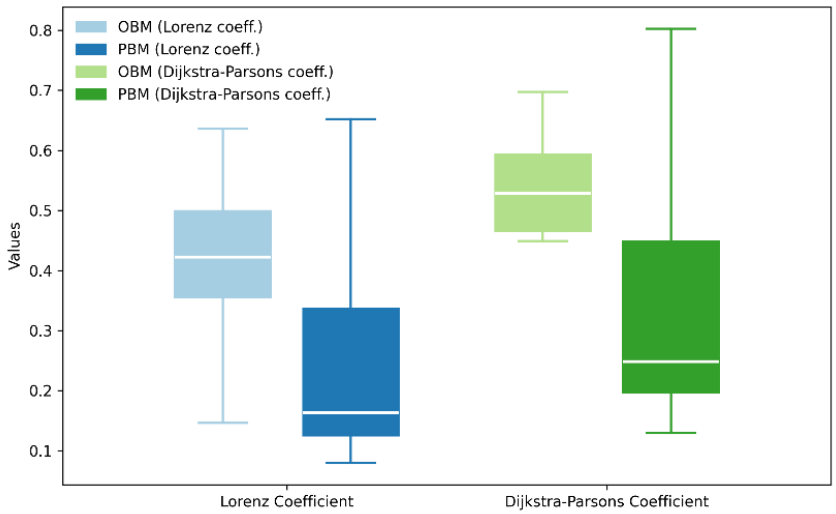


Figure 2. Lorenz coefficient and Dijkstra-Parsons coefficient for total 2710 cropped models

We perform dynamic simulations utilizing the cropped models for 100 years. We show the DUGS system lifetime evaluation and wells' BHP from the dynamic simulations. We evaluate the system lifetime and Levelized Cost of Heat (LCOH) (Figure 3) based on the production temperature, well pressure and energy output. Figure 3 (left) shows that the system lifetime spreads more when the overall N/G ratios are 30% to 70% compared to overall N/G values of 80% and 85% for both PBM and OBM realizations. The LCOH spreading varies significantly at the overall N/G ratio less than 70% although the median value of LCOH is similar for all overall N/G ratios.

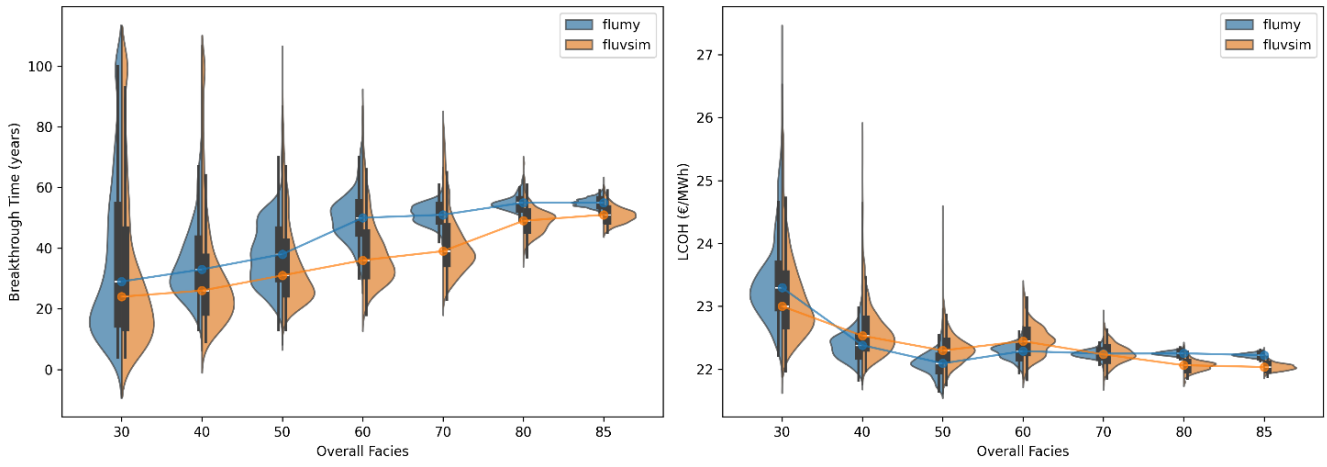


Figure 3. System lifetime and LCOH distribution of the models with different overall N/G ratio where flumy uses the PBM approach and fluvsim uses the OBM approach

3 DISCUSSION

The models created using PBM cover a larger range of LC and DP coefficients with a lower median value compared to the ones using OBM. This range of differences comes from the various arrangements of the sand bodies for these two methods. Although the actual overall N/G ratio range of both cases is the same, the arrangement of reservoir-quality and non-reservoir-quality rock in PBM and OBM is different, which results in a significantly different flow behavior, especially at lower overall N/G ratio. The dissimilarities in the flow behavior results in a different distribution of the system lifetime within each overall N/G ratio. However, the system lifetime converges to the same value for both types of static models when the overall N/G ratio increases to 85%. Based on the current geological modeling assumptions, the convergence of the system lifetime means that there is no need to characterize the geological details within the models after 85% overall N/G ratio. The small perturbation of the LCOH values results in a different median values, although the distribution of LCOH show only minor median value differences. When overall N/G ratios are above 70%, the distributions around the median from the models created by both PBM and OBM become sharp narrow.

4 CONCLUSIONS

In this work, we construct geological facies models using a process-based modeling (PBM) approach and an object-based modeling (OBM) approach to demonstrate the variations in simulating facies distribution of a fluvial depositional environment. The channel geometry and sand body distribution from these two methods diverge significantly. This difference leads to different cropped porosity models that are used in dynamic simulation. Furthermore, even though the porosity distribution in each grouped facies type is the same, the resulting overall porosity distributions diverge substantially due to differences in the channel geometries generated by the two approaches. Our cropped models show that Lorenz coefficient (LC) and Dijkstra-Parsons coefficient (DP) range from 0.06 to 0.72 and from 0.15 to 0.65 for PBM and OBM respectively, covering moderate to high heterogeneity levels. The dynamic simulation results indicate reservoir heterogeneity has a large impact on the production temperature. The system lifetime distributions of the models created from PBM and OBM approaches with different overall N/G ratios are diverging down to an overall N/G ratio close to 85%, above which no isolated sand body remains for either case. Although the LCOH distribution from the models created by PBM and OBM has no clear convergence because of the small variation in absolute LCOH values, the median values of LCOH for each model type are comparable after an overall N/G ratio of 70% or higher. It means when overall N/G ratio becomes equal or larger than 85%, no detailed geological modeling is required under the assumption mentioned in this study.

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